SIX DEGREE OF FREEDOM CONTROL OF PLANAR MOTORS

TECHNICAL FIELD

This invention relates generally to electric motors and more particularly to six degree of freedom control of electric planar motors.

BACKGROUND ART

Electric motors are used in a variety of electrical equipment. For example, wafer stages utilize linear or planar electric motors to position a wafer during photolithography and other semiconductor processing.

U.S. Pat. No. 5,623,853, entitled "Precision Motion Stage with Single Guide Beam and Follower Stage" to Novak et al. and U.S. Pat. No. 5,528,118, entitled "Guideless Stage With Isolated Reaction Stage" to Lee ("the '118 patent") discuss examples of semiconductor fabrication equipment and are incorporated herein by reference in their entireties.

U.S. Pat. No. 4,654,571, entitled "Single Plane Orthogonally Moveable Drive System" to Hinds ("the '571 patent") and U.S. Pat. No. 4,535,278, entitled "Two-Dimensional Precise Positioning Device for Use in a Semiconductor Manufacturing Apparatus" to Asakawa ("the '278 patent") discuss two-dimensional planar electric motors. The motors are two-dimensional in that they have two-dimensional arrays of magnets and armatures instead of magnet tracks and one-dimensional armatures. Further, the magnet arrays and two-dimensional armatures may move with respect to each other in more than two dimensions depending upon the design. Conventional two-dimensional linear motors typically have an array of magnets and an armature having one or more coils disposed on one side of the array of magnets.

The '278 patent describes a three degree of freedom planar motor and a control method for independently producing forces in the X, Y and θ_z (rotation about Z) directions. The method described in the '278 patent is better suited for a

moving-coil electric planar motor. In a moving magnet array electric planar motor, the '278 patent describes a method of controlling the motor that can only produce force with groups of four coils that are fully within the magnetic field of the magnet array. In other words, only coils which are completely covered by the magnet array are used to generate forces and coils which are only partially covered by the magnet array are not used to generate forces. Thus, to provide three degree of freedom control of the planar motor at every position, the magnet array must be sufficiently large to cover an area of at least 5 by 3 coils such that 4 by 2 coils are always completely within the magnetic field of the magnet array at all times.

A platform is attached to the two-dimensional electric motor such that it can be moved and positioned in two or more dimensions by the electric motor. For example, a wafer stage in semiconductor processing equipment may be attached to a coil array or magnet array of a two-dimensional motor and the two-dimensional motor would control the positioning of the wafer stage.

When used to position a platform, conventional two-dimensional electric motors do not smoothly and accurately position the platform. Presently, a coil array in a typical two-dimensional electric motor moves with respect to a stationary magnet array. As exemplified in the '571 patent, cables and hoses are attached to the coil assembly to supply electrical current and coil cooling fluid or air supply to the coils, respectively. However, the hoses and cables impede free motion of the coil assembly.

It is desirable to provide an accurate and efficient method of independently controlling a planar electric motor such that it can be driven to position the platform in six degrees of freedom. It is also be desirable to provide a planar electric motor whose accuracy in positioning is not limited by wiring and/or coil coolant hoses.

SUMMARY OF THE INVENTION

The invention comprises a system and method for independently controlling electric planar motors to move and position in six degrees of freedom. The electric planar motor of the invention is preferably a moving magnet array electric motor comprising a magnet array and a coil array. The current supplied through coils of the coil array interacts with the magnetic field of the magnets of the magnet array to generate forces between the magnet and coil arrays. The generated forces provide motion of the magnet array relative to the coil array in a first, second and third directions generally orthogonal to each other, as well as rotation about the first, second and third directions. The invention teaches the levels of current to be applied to the coils to achieve accurate control of the electric planar motor in six degrees of freedom.

The controlling method of the invention is achieved by the interaction of current in the coil and a magnetic field associated with the magnet. The method for controlling a planar electric motor having a magnetiv array and a coil array for positioning in six degrees of freedom, includes (1) determining the currents to be applied to the coils to generate forces between the magnet array and the coil array in a first (X), second (Y), and third (Z) directions, (2) determining a resultant torque about the first, second, and third directions between the magnet array and the coil array generated by the forces generated by the determined currents; (3) determining current adjustments to compensate for or cancel out the resultant torque; and (4) applying a sum of the determined currents and determined current adjustments to the coils to interact with the magnetic fields of the magnet array.

The method for controlling a planar electric motor for positioning in six degrees of freedom may further include determining the position of the magnet array relative to the coil array and using the determined position to determine currents, resultant torque or current adjustments. The currents to be applied to coils in the portion of the coil array may be selected from sinusoidal, triangular and square waveforms. The method may further include determining the forces to be generated between the magnet array and the coil array in the X, Y, and Z directions to result in forces in the X, Y and Z directions or torques about X, Y,

and Z directions. The current adjustment is preferably determined for each coil in the portion of the coil array.

The invention utilizes all of the coils within the magnetic field of the magnet array, including those which are only partially within the magnetic field of the magnet array. Thus, the currents to be applied to the coils are determined only for coils in the portion of the coil array that is within the magnetic field of the magnetic array, including those coils which are only partially within the magnetic field of the magnet array and the sum of the determined currents and determined current adjustments is applied only to coils in that same portion of the coil array.

The magnet array of the invention covers an area equivalent to at least three four-coil sets or groups or a total of twelve coils. Preferably, the magnet array of the invention covers an area equivalent to at least four four-coil groups for a total of sixteen coils and is preferably square. Thus, the magnetic field of the magnet array of such size interacts with a maximum of twenty-five coils, wholly or partially. In other words, a magnet array of such size covers portions of twenty-five or fewer coils.

In another aspect of the invention, a method for positioning a wafer in a lithography system is provided. The method includes: (1) providing a frame, a stage for supporting the wafer and movable to position the wafer relative to the frame in six degree of freedom, a coil array attached to the frame, and a magnet array adjacent a portion of the coil array, the magnet array being attached to the stage and having magnets generally disposed in a plane, the plane defining a first and second direction; (2) determining currents to be applied to coils in the portion of the coil array to generate forces between the magnet array and the coil array in the first, second, and third directions; (3) determining a resultant torque about the first, second, and third directions between the magnet array and the coil array generated by the forces; (4) determining current adjustments to compensate for the resultant torque; and (5) applying a sum of the currents and current adjustments to the coils to interact with magnetic fields of the magnet array.

In another aspect of the present invention, a planar motor is provided. The planar motor includes (1) a first member; (2) a second member that interacts with the first member to generate driving force, the second member being movable relative to the first member in six degrees of freedom including a first, second, and third directions by the driving force; and (3) a controller connected to at least one of the first member and second member, the controller determining information related to resultant torque about the first, second, and third directions between the first member and the second member.

The planar electric motor and its control method may also be used in a positioning device. The positioning device has a support member such as a stage, a magnet array, and a coil array. In a moving magnet planar motor, the support member is attached to the moving magnet array and is positionable by the electric motor in six degrees of freedom. Alternatively, the support member is attached to the moving coil array and is positionable by the electric motor in six degrees of freedom.

The method appropriately commutates coils and results in accurate and precise movement and positioning of the stage. The methods provide an electrical current distribution or commutation to the active coils of the coil array to control movement of the magnet array with respect to a coil array. The coils of the coil array are distributed in the first (X) and second (Y) direction with a coil period and the magnets of the magnet array are distributed in the first (X) and second (Y) direction with magnet periods of preferably approximately four-thirds the corresponding coil period, though other magnet period to coil period ratios will work.

The method applies to both moving magnet and moving coil electric motors although the moving magnet array electric motor is preferred. The moving magnet array electric motor provides more accurate positioning than conventional moving coil electric motors. The moving magnet electric motor does not require wire connections or cooling hoses to the moving part of the motor. Conventional two-dimensional electrical motors are moving coil motors having wires and cooling hoses connected to the moving coil array. By

eliminating wires and hose connections to the moving component, positioning devices using the moving magnet array are more accurate than conventional moving coil platforms. However, although the invention is described in terms of a moving magnet array electric motor, the electric motor may be modified to be a moving coil array electric motor wherein the coil array moves relative to the magnet array.

The method of the invention uses the full active area of the coil array to generate force and torque and permits a large magnet pitch. A large magnet pitch allows the use of larger magnets for a given size motor, which generally have greater magnetic flux. Thus, the use of the full active area of the coil array and a large magnet pitch results in improved motor performance.

The invention's electric motors and positioning devices should be useful in environments requiring precise and wide ranges of positioning. The electric motor and method of the invention is particularly useful in positioning wafers in semiconductor fabrication processes.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a perspective view of a moving magnet electric motor in accordance with one aspect of the invention;

FIG. 2 shows a perspective view of a magnet array of the moving magnet electric motor of **FIG. 1**;

FIG. 3 shows a perspective view of a coil array of a moving coil electric motor in accordance with another aspect of the invention;

FIG. 4 shows a plan view of a magnet array for use with the coil array of the moving coil electric motor shown in **FIG. 3**;

FIG. 5 is a schematic illustrating a method to achieve force and motion of a portion of a magnet array relative to a portion of a coil array in X and Y directions and rotation about the Z direction in accordance with a method of the invention;

FIG. 6 is a side cross-sectional view of a section of the electric motor of **FIG. 5**

FIG. 7 is a schematic of four coil groups illustrating the phases of the coils;

FIG. 8 is a schematic of a group of four coil illustrating the coordinate system of each coil group;

FIG. 9A depicts a schematic top view of a stage moving over four coil groups illustrating position and force vectors of the coils;

FIG. 9B depicts a schematic top view of the stage covering the coil groups for illustrating a compensation scheme by the partially covered coils;

FIG. 10 is a flow chart of a process to achieve control and motion of a planar motor in six degrees of freedom in accordance with the invention; and

FIG. 11 shows a schematic side view of an example of a photolithography system using the electric motor of the invention.

DESCRIPTION OF THE INVENTION

The invention comprises a system and method for independently controlling electric planar motors to move and position in six degrees of freedom. The following description is presented to enable any person skilled in the art to make and use the invention. Descriptions of specific applications are provided only as examples. Various modifications to the preferred embodiment will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Thus, the invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed herein.

FIG. 1 illustrates a moving magnet electric motor (planar motor) **20** in accordance with one aspect of the invention. The electric motor **20** has a coil array **22** and a magnet array **24**. Electric current is supplied to the coils **26** of the coil array **22**. The current interacts with the magnetic flux of the magnets of the magnet array **24** to generate forces between the coil array **22** and the magnet array **24**. The forces move and position the magnet array **24** relative to the coil array

22. The invention teaches the levels of current to be applied to the coils **26** to achieve six degree of freedom control of the electric motor (planar motor) **20**.

As shown in **FIG. 1**, a surface of the coil array **22** is in proximity to an opposing surface of the magnet array **24** during operation of the electric planar motor **20**. Preferably, the opposing faces of the coil and magnet arrays **22, 24** are separated by several mm or less during operation. One or more air bearings (not shown) may be provided to separate the coil array **22** from the magnet array **24**. Other types of bearings, such as magnetic bearings, may be utilized. Construction and usage of an air bearing are known to those skilled in the art. For example, the '571 patent teaches an air bearing adaptable for use in the invention. The air bearing may position the coil array **22** and the magnet array **24** at a neutral position about which the coil array **22** and the magnet array **24** can move relative to each other in six degrees of freedom.

When one or more air bearings separate the coil array **22** and the magnet array **24** relative to each other, the coil array **22** and/or the magnet array **24** may be potted with any suitable material such as epoxy or may be covered with a flat plate made of, for example, ceramic, composite, or metal, to form generally flat surfaces. The generally flat surfaces improve performance of the air bearing in separating or levitating the coil array **22** and magnet array **24** relative to each other.

Coils **26** of the coil array **22** are periodically distributed in X (first) direction and Y (second) directions. The coil array **22** has a first coil period; **28** in the X direction defined as the distance from the center of one coil to the center of an adjacent coil along the X direction. The coil array **22** further has a second coil period **30** in the Y direction defined as the distance from the center of one coil to the center of an adjacent coil along the Y direction. The coil period **28** in the X direction is preferably approximately equal to the coil period **30** in the Y direction.

As shown in **FIG. 1**, each coil **26** in the coil array **22** has approximately the same shape and size. Although the coils **26** having approximately the same shape and size are preferred, the coils of the coil array **22** may have varying

shapes and/or sizes. Each coil **26** preferably covers as much of an area of one coil period in both the X and Y directions as possible in order to maximize the force generated from the interaction between the magnet array **24** and the coil array **26** and thus minimizes the coil power input necessary to achieve a desired amount of force. A rectangular profile of the coil **26** maximizes the area occupied by each coil **26** within the area defined by the coil periods **28, 30** and thus is preferred. As is evident, when the periods **28** and **30** are approximately equal, the profile of the coil **26** approximates a square.

Each coil **26** may be disposed about a magnetically impermeable post **32**. The magnetically impermeable post **32** facilitates mounting and aligning coil **26** without distorting the magnetic field. In contrast, a magnetically permeable post would focus a magnetic field created by the coil **26** and produce an uneven field distribution over the outline of the coil **26**.

A backing panel **34** may be attached to one surface or side of the coil array **22**. The backing panel **34** may comprise a magnetically permeable material such as iron or may comprise a magnetically impermeable material such as plastic or ceramic. A magnetically permeable backing panel **34** increases the permanent magnetic flux through the coils and thus increases the performance of the electric planar motor **20**.

As shown in **FIG. 1**, the coil array **22** has a first coil array dimension **36** in the X direction and a second coil array dimension **38** in the Y direction. Also, the magnet array has a first magnet array dimension **40** in the X direction and a second magnet array dimension **42** in the Y direction. As is evident, the first coil array dimension **36** is larger than the first magnet array dimension **40** and second coil array dimension **38** is larger than the second magnet array dimension **42**.

FIG. 2 is a perspective view of the magnet array **24**, illustrating the surface or side of the magnet array **24** which faces the coil array **22** during operation of the electric motor (planar motor) **20**.

Similar to the coils of the coil array **22**, magnets in the magnet array **24** are also periodically distributed in two directions. The magnet array has a first magnet period **44** in the X direction defined as the distance from the center of one

magnet to the center of the next magnet having the same polarity along the X direction. The magnet array **24** further has a second magnet period **46,** in the Y direction, which is the distance from the center of one magnet to the center of the next magnet having the same polarity along the Y direction.

The magnet periods **44, 46** of the magnet array **24** in the X and Y directions are related to the periods **28, 30** of the coil array **22** in the X and Y directions, respectively. Specifically, the first magnet period **44** in the X direction is a approximately four-thirds of the first coil period **28** in the X direction. Further, the second magnet period **46** in the Y direction is approximately four-thirds of a second coil period **30** in the Y direction. Thus, when the coil periods **28, 30** in the X and Y directions are approximately equal, the magnet periods **44, 46** in the X and Y directions are also approximately equal.

The magnets are preferably attached to a magnetically permeable backing **48**. The magnetically permeable backing **48** completes flux paths between adjacent magnets of opposite polarities to increase the magnetic flux of each polarity, as will be described in more detail below.

Preferably, the magnets in the magnet array **24** alternate in polarity in both the X and the Y directions such that the magnets along any diagonals of the X and the Y directions are of the same polarity. The interior magnets **50** in the magnet array **24** preferably have the same magnetic flux. In contrast, non-corner edge magnets **52** and corner magnets **54, 56, 58, 60** of the magnet array **24** have a fraction of the magnetic flux of the interior magnets **50**. For example, the non-corner edge magnets **52** of the magnet array **24** have approximately one-half the magnetic flux of the interior magnet **50**. The corner magnets **54, 56, 58, 60** have one-quarter the flux of the interior magnets **50**. The edge and corner magnets may have any other suitable fractional magnetic fluxes relative to the magnetic fluxes of the interior magnets **50**. The fractional fluxes for the non-corner edge magnets **52** and for the corner magnets **54, 56, 58, 60** complete flux paths with each other and with the interior magnets **50** while simultaneously minimizing fringe magnetic fields at the edges of the magnet array **24**. Without the fractional magnetic fluxes of the edge and corner magnets, the fringe magnetic fields at the

magnet array edges may otherwise degrade performance of the moving magnet electric motor.

Other types and arrangements of the magnets may also be used in the control method of the invention. For example, wedge magnets may be utilized to facilitate the completion of the magnetic fields. Magnet arrays using wedge magnets are disclosed in, for example, U.S. Patent No. 6,188,147, entitled "Wedge and Transverse Magnet Arrays", issued on February 13, 2001, by Hazelton et al. and copending application Serial No. 09/309,721, entitled "Planar Electric Motor and Positioning Device Having Transverse Magnets", filed on May 11, 1999, both of which are incorporated herein by reference.

The moving magnet planar motor **20** is generally preferable to a moving coil electric motor because the moving magnet array **24** does not require electrical current connections or hoses to carry cooling fluids. Wires and hoses connected to a coil array of the moving coil electric motor may interfere with the motion of the coil array with respect to the magnet array in a moving coil planar motor. Nonetheless, the method of controlling an electric planar motor in six degrees of freedom of the invention as described below may also be applied to a moving coil planar motor, such as shown in **FIGS. 3** and **4**.

FIGS. 3 and **4** show, respectively, a coil array **122** and a magnet array **124** of a moving coil planar motor **120** according to another aspect of the invention. The coil array **122** is movable relative to the magnet array **124** by supplying electric current to one or more of the coils **126** of the coil array **122**. The current interacts with the magnetic flux of the magnets of the magnet array **124** to generate forces between the coil array **122** and the magnet array **124**. The forces move and position the coil array **122** relative to the magnet array **124**.

A face or side **162** of the coil array **122** is in close proximity to the face or side of the magnet array **124** shown in **FIG. 4** during operation of the electric planar motor **120**. Preferably, the opposing faces of the coil and magnet arrays **122, 124** are separated by a few mm or less during operation. One or more air bearings **164**, as described above with reference to the moving magnet motor **20**, may be provided to separate the coil array **122** from the magnet array **124**. In

addition, when one or more air bearings **164** separate the coil array **122** and the magnet array **124** relative to each other, the coil array **122** and/or the magnet array **124** may be potted or covered with a flat plate, as described above, to form generally flat surfaces. The generally flat surfaces improve performance of the air bearing in separating or levitating the coil array **122** and magnet array **124** relative to each other.

Coils **126** of the coil array **122** are periodically distributed in X (first) direction and Y (second) directions. The coil array **122** has a first coil period **128** in the X direction defined as the distance from the center of one coil to the center of an adjacent coil along the X direction. The coil array **122** further has a second coil period **130** in the Y direction defined as the distance from the center of one coil to the center of an adjacent coil along the Y direction. The coil period **128** in the X direction is preferably approximately equal to the coil period **130** in the Y direction.

Similar to the coils **26** of the coil array **22** of the moving magnet planar motor **20**, each coil **126** may be disposed about a magnetically impermeable post **132**. Further, a backing panel **134** may be attached to one surface or side of the coil array **122**.

The magnets are preferably attached to a magnetically permeable backing **148**. The magnetically permeable backing **148** completes flux paths between adjacent magnets of opposite polarities to increase the magnetic flux of each polarity, as will be described in more detail below.

As shown in **FIG. 4**, the magnets in the magnet array **124** are also periodically distributed in the X and Y directions. The magnet array has a first magnet period **144** in the X direction defined as the distance from the center of one magnet to the center of the next magnet having the same polarity along the X direction. The magnet array **124** further has a second magnet period **146** in the Y direction defined as the distance from the center of one magnet to the center of the next magnet having the same polarity along the Y direction.

Preferably, the magnets in the magnet array **124** alternate in polarity in both the X and the Y directions such that the magnets along any diagonals of the

X and the Y directions are of the same polarity. The first magnet period **144** in the X direction is preferably approximately four-thirds of the first coil period **128** in the X direction. Further, the second magnet period **146** in the Y direction is approximately four-thirds of a second coil period **130** in the Y direction. Thus, when the coil periods **128, 130** in the X and Y directions are approximately equal, the magnet periods **144, 146** in the X and Y directions are also approximately equal.

In the moving coil planar motor **120**, the total number of coils in the coil array **122** is preferably a multiple of 4. As will be described below with reference to **FIG. 5**, the principles of operation for control and movement in six degrees of freedom in the X, Y, and Z directions and rotation about the X, Y, and Z directions use four sets of four adjacent, approximately identically shaped coils.

The above-described planar motors **20, 120** are similar to those described in U.S. Patent No. 6,208,045 entitled "Electric Motors and Positioning Devices Having Moving Magnet Arrays and Six Degrees of Freedom", issued on March 27, 2001 by Hazelton et al., the entirety of which is incorporated herein by reference.

Control in Six Degrees of Freedom

The interactions of currents in the coils and magnetic flux of the magnets in the magnet array to generate forces between the magnet array and the coil array will now be described. Although the following description is in terms of a moving magnet electric motor **20**, as is preferred, similar concepts and principles may be used in a moving coil electric motor **120**.

A general qualitative description of the control of the moving magnet motor in three degrees of freedom will be described with reference to **FIG. 5**. **FIG. 5** is a schematic representation of a section of the moving magnet electric motor **20**. The three degrees of freedom are in the X and Y directions and rotation about the Z direction. A general qualitative description of the control of the moving magnet motor in six degrees of freedom will be described with reference to **FIG. 6**. **FIG. 6** is a side cross-sectional view of a portion of the

electric motor section of **FIG. 5**. The six degrees of freedom are in the X, Y, and Z direction and rotation about the X, Y, and Z directions.

FIG. 5 shows a sub-array of the magnet array **24** and a set of four coils **200, 202, 204, 206** which are part of the coil array **22**. In the embodiment shown in **FIG. 5**, each coil has first and second coil periods **28, 30** in the X and Y directions, respectively, approximately equaling three-fourths of first and second magnet periods **44, 46**, respectively.

By appropriately commutating currents flowing in the coils **200, 202, 204, 206**, force is generated between the coil array **22** and the magnet array **24**. For example, in the relative positions of the coil and magnet arrays **22, 24** shown in **FIG. 5**, a counter-clockwise current **208** supplied through coil **200** interacts with the magnetic field of the magnets covered by the coil **200** to exert a force on the coil array **22,** in a positive X direction as indicated by arrow **210**, according to the right-hand rule and the Lorentz force laws.

In a two-phase commutation scheme to generate a force between the coil and magnet arrays **22, 24** in the positive X direction **210**, two coils **200, 202** are commutated. For example, in the relative positions of the coil and magnet arrays **22, 24** shown in **FIG. 5**, the counter-clockwise current **208** supplied through the coil **200** is at a maximum while no current is supplied through the coil **202**. As the coil **200** moves in the positive X direction **210** and its center **200c** approaches the next magnetic pole **212**, the counter-clockwise current **208** supplied through the coil **200** approaches zero. As the coil **200** moves in the positive X direction **210**, the coil **202** also moves in the direction **210**, and its center **202c** moves toward location **214**.

To maintain the force in the positive X direction **210**, a counter-clockwise current is supplied through the coil **202**. The counter-clockwise current in the coil **202** increases sinusoidally to its maximum. When the center **202c** of coil **202** coincides with the location **214**, the current in the coil **202** will be at its maximum.

Similarly, current can be commutated to flow in clockwise direction **216** through the coil **204** to generate a force on the coil array **22** in a negative Y

direction **218**. As in the movement in the positive X direction **210**, the coils **202, 204** may be commutated in a similar fashion as the coils **200, 202** to provide a continuous force in the negative Y direction **218**. As with the coils **200, 202**, the commutation of the coils **202, 204** is a two phase commutation.

With respect to coil **206**, magnets **220, 222, 224, 226** are symmetrically positioned about its center **206c**. When the coil **206** is symmetric about its center **206c** and the coil center **206c** is centrally disposed over the magnets **220, 222, 224, 226**, the forces generated by the interaction between the current through the coil **206** and the magnetic fields of the magnets **220, 222, 224, 226** are cancelled. Thus, unlike the other three coils **200, 202, 204**, the coil **206** cannot generate a force between the coil and magnet arrays **22, 24** in the position as shown in **FIG. 5.**

Only a few examples of commutation have been described. Clearly, as will be appreciated by those skilled in the art, many other commutations may be applied to the coils **200, 202, 204, 206** and the other coils in the coil array **22** to achieve forces and motions in X and Y directions. By providing at least two sets of four coils and by simultaneously generating forces in both the X and Y directions, such as in the positive X and negative Y directions **210 and 218** respectively, the electric motor **20** can also be controlled to rotate the moving magnet array **24** relative to the stationary coil array **22** about the Z direction.

Referring now to **FIG. 6** the commutation of the coils to generate a force in the Z direction will now be described, enabling six degree of freedom control of the planar motor. By selectively generating forces in the Z direction, torques about the X and Y directions can be achieved.

FIG. 6 is a side cross-sectional view of a portion of the electric motor section of **FIG. 5** showing the coils **200** and **202** of either a moving coil or moving magnet electric motor. The coil **202** comprises coil portions **202a** and **202b** about its center **202c**. Similarly, coil **200** comprises coil portions **200a** and **200b** about its center **200c**. The coil **202** experiences nonvertical components of magnetic flux density **B** when the magnet is at off-center locations relative to a coil portion, such as coil portions **202a, 202b**. A current is applied to the coil **202**

which flows through coil portion **202a** in a direction into the plane of **FIG. 6** and through coil portion **202b** in a direction out of the plane of **FIG. 6**. Nonvertical components of the magnetic flux density **B** interact with the current flowing through the coil portions **202a** and **202b** to produce forces $\mathbf{F}_{202a}$ and $\mathbf{F}_{202b}$, respectively, in the Z direction.

In a two-phase commutation scheme to exert force on the coil array in the Z direction relative to the magnet array, the coils **200** and **202** are commutated. For example, in the position shown in **FIG. 6**, the current through the coil **202** is at a maximum while the coil **200** has no current flowing through it. When the coil **202** is moved in the X direction and its coil portion **202a** approaches magnetic pole **228**, the current through the coil **202** will approach zero. As the coil **202** moves in the X direction, the coil **200** also moves in the X direction and its center portion **200c** moves toward a position directly below magnetic pole **212**.

To maintain the force in the Z direction, the current in the coil **200** is commutated which flows through coil portion **200a** in a direction out of the plane of **FIG. 6** and through coil portion **200b** in a direction into the plane of **FIG. 6**. The current applied to coil **200** will be approximately 90° out of phase relative to the current applied to coil **202**. The current in the coil **200** increases sinusoidally to its maximum. When the center **200c** of coil **200** is directly below magnet pole **212**, the current in the coil **200** will be at its maximum.

Only a few examples of commutation have been described. Clearly, as will be appreciated by those skilled in the art, many other commutations may be applied to the coils **200, 202, 204, 206** and the other coils in the coil array **22** to achieve force and motion of the coil array **22** with respect to the magnet array **24** in six directions: in the X, Y, Z directions and rotation about the X, Y, Z directions.

A more detailed quantitative description of the control of the moving magnet motor in six degrees of freedom with torque control will now be described with reference to **FIGS. 7-9**.

The current commutation scheme is applied to the coils within the magnetic field of the magnets of the magnet array **22**. These are referred to as the

active coils and include coils which are only partially within the magnetic field of the magnets of the magnet array **22**. The current supplied through the active coils interact with the magnetic field of the magnet array **24** to generate a force between the magnet and coil arrays **22, 24**. No current is applied to the inactive coils, coils that are not within the magnetic field of the magnets of the magnet array **22**. Thus, all coils that are wholly or partially within the magnetic field of the magnet array **24** are utilized to generate forces to control the stage in six degrees of freedom.

The utilization of coils only partially within the magnetic field of the magnet array **24** maximizes the forces generated. Further, it allows the utilization of a smaller magnet array **24**. Specifically, the magnet array **24** needs to only cover the size of three sets or groups of four coils or a total of twelve coils in order to control the magnet array **24** in six degrees of freedom.

The following derivation of the coil current commutation scheme to control the moving magnet motor **20** in six degrees of freedom is described in terms of a magnet array covering a square of four by four coils. When all four edges of the magnet array or stage are aligned with the edges of the four by four set of coils, the stage completely covers or overlaps with 16 coils. When two of the four edges of the stage are aligned with the edges of the four by four set of coils, the stage completely covers 12 coils and partially covers 8 coils. When none of the four edges of the stage are aligned with the edges of the four by four set of coils, the stage completely covers 9 coils and partially covers 16 coils, for a total of 25 coils. As is evident, in each case, the stage covers an equivalent of 16 full coils.

To achieve six degree of freedom control of the moving magnet motor, the coils need to generate forces in the X, Y, Z directions. As is evident, forces in the X ,Y, and Z directions provides linear control and movement in the X, Y , and Z directions. These forces can also generate torques about the X, Y, and Z axes, since there are multiple coils at different X, Y positions. For example, two coils separated in the X direction can produce different amounts of Z force to create a torque about the Y axis.,

As shown in **FIG. 7**, the planar motor has four phases **A, B, C,** and **D** and is essentially a four-phase device. The phase of each coil is defined by the relative positions and polarities of the magnets covered by the coil. The negative sign associated with a given phase indicates that the coil covers similarly positioned magnets with polarities opposite those of the same phase without a negative sign. For example, a B phase coil covers the same number and position of magnets as a -B phase coil but with opposite polarities.

To enable six degree of freedom control of the planar motor, moving magnet array or stage must cover an area of twelve coils. Preferably, the area is of sixteen coils, and square of four by four coils. However, other shapes of the magnet array may be utilized, such as a L-shaped, cross-shaped or T-shaped.

TORQUE CONTROL

In the following derivation of a commutation scheme, the notations of the various parameters are first defined. The torque generated between a single four-coil group and the magnet array is then determined. Finally, the torque generated between the four coil groups and the magnet array or stage is determined. The torque-compensated commutation scheme allows accurate and precise control and positioning of the stage in six degrees of freedom.

Notation

In the following derivation of the coil current commutation scheme to control the moving magnet motor **20** in six degrees of freedom, various parameters, vectors, and matrices are defined in **Tables I, II,** and **III**, respectively. Subscripts ***A, B,*** *C*, and ***D*** denote the four coil phases in a coil group. Subscripts ***1, 2, 3,*** and ***4*** denote each of the four coil groups under the stage.

TABLE I	
Scalar Parameter	**Definition**
x, y, z	position of the center of gravity of the stage relative to peak-force position
r_x, r_y, r_z	components for the vector **r**
p_{xi}, p_{yi}, p_{zi}	components of the vector $\mathbf{p}_i$
R_x, R_y, R_z	desired forces for the entire stage in the X, Y and Z directions, respectively
$\Delta_x, \Delta_y, \Delta_z$	magnitude of correction or adjustment factors for X, Y, and Z torque

TABLE II		
Vector	**No. of Elements**	**Definition**
I	4	currents in each coil of a coil group
r	3	desired force vector for a coil group in the X, Y, and Z directions
f	3	force vector produced by a coil group
t	3	torque vector produced by a coil group, measured at the origin of the coil group
y	6	output force and torque vector produced by a coil group
$\mathbf{q}_i$	3	position vector from the center of gravity of the stage to the origin of coil group i in the X, Y, and Z directions
F	3	force vector produced by the entire stage
t	3	torque vector produced by the entire stage (measured at the center of gravity of the stage)
Y	6	force and torque output vector produced by the entire stage

TABLE III		
Matrix	**Size**	**Definition**
C	4 x 3	commutation matrix; same for all coil groups
$\mathbf{K}_f$	3 x 4	force constant matrix; same for all coil groups
$\mathbf{K}_t$	3 x 4	torque constant matrix; same for all coil groups
K	6 x 3	input-output matrix for a coil group; same for all coil groups
p	3 x 4	position vectors (each column) for each coil in a group, relative to the origin of the group; same and constant for all coil groups
A	6 x 6	input-output matrix for the complete stage

Force Resulting From Open Loop Commutation for the Coil Group

As shown in **FIG. 8**, an origin for the four-coil group can be arbitrarily defined as the center of the A-phase (lower-left) coil. A different origin may be selected, preferably at the center of one of the other coils in the coil group. A current vector **I** for the currents in the four coils may be obtained by multiplying a commutation matrix **C**, which depends only on the X-Y position of the stage, by the desired force vector **r**:

$$\mathbf{I} = \mathbf{Cr} = \begin{bmatrix} \sin(x)\cos(y) & \cos(x)\sin(y) & \cos(x)\cos(y) \\ \cos(x)\cos(y) & -\sin(x)\sin(y) & -\sin(x)\cos(y) \\ -\sin(x)\sin(y) & \cos(x)\cos(y) & -\cos(x)\sin(y) \\ -\cos(x)\sin(y) & -\sin(x)\cos(y) & \sin(x)\sin(y) \end{bmatrix} \begin{Bmatrix} r_x \\ r_y \\ r_z \end{Bmatrix}$$

The above equation assumes a commutation sinusoidal waveform although other waveforms such as square and/or triangular waveforms, may be utilized.

The force constant for a group of coils is given by:

$$\mathbf{K}_f = \begin{bmatrix} \sin(x)\cos(y) & \cos(x)\cos(y) & -\sin(x)\sin(y) & -\cos(x)\sin(y) \\ \cos(x)\sin(y) & -\sin(x)\sin(y) & \cos(x)\cos(y) & -\sin(x)\cos(y) \\ \cos(x)\cos(y) & -\sin(x)\cos(y) & -\cos(x)\sin(y) & \sin(x)\sin(y) \end{bmatrix}$$

Matrix $\mathbf{K}_f$ is simply the transpose of matrix $\mathbf{C}$, or $\mathbf{C}^T$. The four columns of matrix $\mathbf{K}_f$ are force-constant vectors for the four coils in the group and the three rows are components corresponding to coordinates X, Y and Z.

The force $\mathbf{f}$ produced by the coil group can be found by multiplying the force-constant matrix $\mathbf{K}_f$ by the current vector $\mathbf{I}$:

$$\mathbf{f} = \mathbf{K}_f\mathbf{I}$$

After simplification, the equation for force $\mathbf{f}$ is simplified to:

$$\mathbf{f} = \begin{Bmatrix} r_x \\ r_y \\ r_z \end{Bmatrix} = \mathbf{r}$$

The above result shows that with the commutation law used, a group of four coils can produce any desired force vector. If the commutation waveform were perfectly sinusoidal and the magnets were perfectly symmetrical, there would be no force ripple as the stage moves.

Torque Resulting From Open Loop Commutation for the Coil Group

Torque $\mathbf{t}$ is defined to be about the origin of the coil group. The basic equations for torque $\mathbf{t}$ are given by:

$$\mathbf{t} = \mathbf{p} \times \mathbf{f}$$
$$\mathbf{t} = \mathbf{p} \times \left(\mathbf{K}_f\mathbf{I}\right)$$

Factoring out the current $\mathbf{I}$ results in similar equations for the torque constant $\mathbf{K}_t$:

$$\mathbf{K}_t = \mathbf{t}\mathbf{I}^{-1}$$
$$\underline{\mathbf{K}_t = \mathbf{p} \times \mathbf{K}_f}$$

A position vector is defined as the vector extending from the origin of the coil group to the center of each coil. Position matrix $\mathbf{p}$ is given by:

$$\mathbf{p} = \begin{bmatrix} 0 & \frac{3\pi}{2} & 0 & \frac{3\pi}{2} \\ 0 & 0 & \frac{3\pi}{2} & \frac{3\pi}{2} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The four columns of the **p** matrix are the position vectors for the four coils of the coil group.

Matrix $\mathbf{K}_t$ may be determined by taking the cross-products of each column of **p** with the respective column of $\mathbf{K}_f$. This cross-product is:

$$\mathbf{K}_t = \frac{3\pi}{2}\begin{bmatrix} 0 & 0 & -\cos(x)\sin(y) & \sin(x)\sin(y) \\ 0 & \sin(x)\cos(y) & 0 & -\sin(x)\sin(y) \\ 0 & -\sin(x)\sin(y) & \sin(x)\sin(y) & \cos(x)\sin(y)-\sin(x)\cos(y) \end{bmatrix}$$

The torque **t** produced by the group of coils can be expressed by the following equations:

$$\mathbf{t} = \mathbf{K}_t\mathbf{I} = \mathbf{K}_t\mathbf{C}\mathbf{r}$$

$$\mathbf{t} = \frac{3\pi}{2}\begin{bmatrix} 0 & -\sin(y)\cos(y) & \sin^2(y) \\ \sin(x)\cos(x) & 0 & -\sin^2(x) \\ -\sin^2(y) & \sin^2(x) & 0 \end{bmatrix}\begin{Bmatrix} r_x \\ r_y \\ r_z \end{Bmatrix}$$

Given that the coil group as a whole has three inputs (the three components of the desired force vector) and six outputs (the three components of each of the force and torque vectors), the equations for **f** and **t** can be rewritten as:

$$\begin{Bmatrix} f_x \\ f_y \\ f_z \\ t_x \\ t_y \\ t_z \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{3\pi}{2}\sin(y)\cos(y) & \frac{3\pi}{2}\sin^2(y) \\ \frac{3\pi}{2}\sin(x)\cos(x) & 0 & -\frac{3\pi}{2}\sin^2(x) \\ -\frac{3\pi}{2}\sin^2(y) & \frac{3\pi}{2}\sin^2(x) & 0 \end{bmatrix}\begin{Bmatrix} r_x \\ r_y \\ r_z \end{Bmatrix} \quad (1)$$

Denoting the six-element vector containing forces and torques as **y** and the six by three matrix **K**, the above equation can be rewritten as:

$$\mathbf{y} = \mathbf{K}\mathbf{r}$$

The Complete Stage: Four Four-Coil Groups

FIG. 9A is a schematic of a stage or magnet array **24** moving over four four-coil groups of the coil array **22** illustrating position and force vectors of the coils. The position vectors **q** point from the center of gravity of the stage to the origin of each of the four coil groups.

As noted above, the stage may cover up to 25 coils, some partially and some completely. The effects of the partially covered coils is simplified in the following analysis. For example, in the lower left coil group **300** shown in **FIG. 9B**, three of the coils are partially covered and one of the coils is completely covered. The three partially covered coils generate only a fraction of the force they would otherwise generate.

The difference in the force generated is compensated by two partially covered coils **302** above the upper left coil group, two partially covered coils **304** to the right of the lower right coil group, and one partially covered coil **306** in the far upper right corner. Including this effect in the analysis would change the **K** matrices because the moment arms for the partial coils would be different. However, matrix **K** can still be obtained for each coil group as a function of stage position.

The complete stage covers or interacts with an equivalent of four coil groups. Each coil group has an independent set of three inputs (the components of the vector **r**, the desired force vector) and six outputs (the components of **y**, the output force and torque vector). As noted above, subscripts ***1, 2, 3,*** and ***4*** reference each of the four coil groups under the stage.

Vector $\mathbf{q}_i$ is defined as the position vector extending from the center of gravity of the stage to the origin of the coil group ***i***. Using this notation, the total force and torque **Y** on the stage can be expressed as:

$$\mathbf{Y}=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -q_{z1} & q_{y1} & 1 & 0 & 0 \\ q_{z1} & 0 & -q_{x1} & 0 & 1 & 0 \\ -q_{y1} & q_{x1} & 0 & 0 & 0 & 1 \end{bmatrix}\mathbf{y}_1+\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -q_{z2} & q_{y2} & 1 & 0 & 0 \\ q_{z2} & 0 & -q_{x2} & 0 & 1 & 0 \\ -q_{y2} & q_{x2} & 0 & 0 & 0 & 1 \end{bmatrix}\mathbf{y}_2+\ldots$$

Defining each of the six by six matrices $\mathbf{Q}_i$, the above equation can be rewritten as:

$$\mathbf{Y} = \sum_4 \mathbf{Q}_i \mathbf{y}_i$$

$$\mathbf{Y} = \sum_4 \mathbf{Q}_i \mathbf{K}_i \mathbf{r}_i$$

Table IV lists the components of the position vector **q** and the force vector **r** for each coil group.

TABLE IV						
Group	q_x	q_y	q_z	r_x	r_y	r_z
1	$-\frac{5\pi}{2}-x$	$-\frac{5\pi}{2}-y$	$-z$	R_x	$R_y+\Delta_z$	$R_z+\Delta_x-\Delta_y$
2	$\frac{\pi}{2}-x$	$-\frac{5\pi}{2}-y$	$-z$	R_x	$R_y-\Delta_z$	$R_z+\Delta_x+\Delta_y$
3	$-\frac{5\pi}{2}-x$	$\frac{\pi}{2}-y$	$-z$	R_x	$R_y+\Delta_z$	$R_z-\Delta_x-\Delta_y$
4	$\frac{\pi}{2}-x$	$\frac{\pi}{2}-y$	$-z$	R_x	$R_y-\Delta_z$	$R_z-\Delta_x+\Delta_y$

The adjustyment factors (Δ's) are introduced to compensate for the unwanted torque. The following analysis is intended to explain the relationship among the forces, intended torques and the adjustment factors, which comprises a significant part of the invention.

Torque Generated by the Electric Motor on the Stage

The total torque generate by all four coil groups can be determined by summing the individual coil group torques and the cross product of the position and force vectors for each coil group. This process is detailed below for each component coordinate X, Y, and Z.

Torque About the X-axis

The total torque about the X-axis is:

$$T_x = \sum t_x + \sum \left(q_y f_z - q_z f_y\right) \qquad (2)$$

The first term Σt_x is the X-axis torque about the origin of each coil group. Using the values for the force vector **r** from **Table IV** in equation (1) above, the torque for each of the four coil groups are expressed as:

$$t_{x1} = \frac{3\pi}{2}\left[-\sin(y)\cos(y)\left(R_y + \Delta_z\right) + \sin^2(y)\left(R_z + \Delta_x - \Delta_y\right)\right]$$

$$t_{x2} = \frac{3\pi}{2}\left[-\sin(y)\cos(y)\left(R_y - \Delta_z\right) + \sin^2(y)\left(R_z + \Delta_x + \Delta_y\right)\right]$$

$$t_{x3} = \frac{3\pi}{2}\left[-\sin(y)\cos(y)\left(R_y + \Delta_z\right) + \sin^2(y)\left(R_z - \Delta_x - \Delta_y\right)\right]$$

$$t_{x4} = \frac{3\pi}{2}\left[-\sin(y)\cos(y)\left(R_y - \Delta_z\right) + \sin^2(y)\left(R_z - \Delta_x + \Delta_y\right)\right]$$

Summing these four equations results in the first term Σt_x of the total torque equation:

$$\sum t_x = 4\frac{3\pi}{2}\left(-\sin(y)\cos(y)R_y + \sin^2(y)R_z\right)$$

Substituting the position vector q and force vector r components from **Table IV** into equation (2) results in the following total X-axis torque equation:

$$\begin{aligned} T_x = \sum t_x &+ \left(\frac{-5\pi}{2} - y\right)\left(R_z + \Delta_x - \Delta_y\right) + z\left(R_y + \Delta_z\right) \\ &+ \left(\frac{-5\pi}{2} - y\right)\left(R_z + \Delta_x + \Delta_y\right) + z\left(R_y - \Delta_z\right) \\ &+ \left(\frac{\pi}{2} - y\right)\left(R_z - \Delta_x - \Delta_y\right) + z\left(R_y + \Delta_z\right) \\ &+ \left(\frac{\pi}{2} - y\right)\left(R_z - \Delta_x + \Delta_y\right) + z\left(R_y - \Delta_z\right) \end{aligned}$$

This equation simplifies to:

$$T_x = 4\left[\left(-\frac{3\pi}{2}\sin(y)\cos(y) + z\right)R_y + \left(\frac{3\pi}{2}\sin^2(y) - \pi - y\right)R_z - \frac{3\pi}{2}\Delta_x\right]$$

Torque About the Y-axis

Similarly, the torque about the Y-axis can be found from:

$$T_y = \sum t_y + \sum (q_z f_x - q_x f_z) \qquad (3)$$

The first term Σt_y is the Y-axis torque about the origin of each coil group. The Y-axis torque for each coil group can be expressed by:

$$t_{y1} = \frac{3\pi}{2}\left[\sin(x)\cos(x)(R_x) - \sin^2(x)(R_z + \Delta_x - \Delta_y)\right]$$
$$t_{y2} = \frac{3\pi}{2}\left[\sin(x)\cos(x)(R_x) - \sin^2(x)(R_z + \Delta_x + \Delta_y)\right]$$
$$t_{y3} = \frac{3\pi}{2}\left[\sin(x)\cos(x)(R_x) - \sin^2(x)(R_z - \Delta_x - \Delta_y)\right]$$
$$t_{y4} = \frac{3\pi}{2}\left[\sin(x)\cos(x)(R_x) - \sin^2(x)(R_z - \Delta_x + \Delta_y)\right]$$

Summing these four equations results in the first term Σt_y of the total torque equation:

$$\sum t_y = 4\frac{3\pi}{2}\left(\sin(x)\cos(x)R_x - \sin^2(x)R_z\right)$$

Substituting the position vector $\boldsymbol{q}$ and force vector $\boldsymbol{r}$ components from **Table IV** into equation (3) results in the following total Y-axis torque equation:

$$\begin{aligned} T_y = \sum t_y &- zR_x + \left(\frac{5\pi}{2} + x\right)(R_z + \Delta_x - \Delta_y) \\ &- zR_x + \left(\frac{-\pi}{2} + x\right)(R_z + \Delta_x + \Delta_y) \\ &- zR_x + \left(\frac{5\pi}{2} + x\right)(R_z - \Delta_x - \Delta_y) \\ &- zR_x + \left(\frac{-\pi}{2} + x\right)(R_z - \Delta_x + \Delta_y) \end{aligned}$$

This equation simplifies to:

$$T_y = 4\left[\left(\frac{3\pi}{2}\sin(x)\cos(x) - z\right)R_x + \left(\frac{-3\pi}{2}\sin^2(x) + \pi + x\right)R_z - \frac{3\pi}{2}\Delta_y\right]$$

Torque About the Z-axis

Similarly, the torque about the Z-axis can be found from:

$$T_z = \sum t_z + \sum \left(q_x f_y - q_y f_x \right) \qquad (4)$$

The first term Σt_z is the Z-axis torque about the origin of each coil group. The Z-axis torque for each coil group can be expressed by:

$$t_{z1} = \frac{3\pi}{2}\left[-\sin^2(y)R_x + \sin^2(x)\left(R_y + \Delta_z\right)\right]$$
$$t_{z2} = \frac{3\pi}{2}\left[-\sin^2(y)R_x + \sin^2(x)\left(R_y - \Delta_z\right)\right]$$
$$t_{z3} = \frac{3\pi}{2}\left[-\sin^2(y)R_x + \sin^2(x)\left(R_y + \Delta_z\right)\right]$$
$$t_{z4} = \frac{3\pi}{2}\left[-\sin^2(y)R_x + \sin^2(x)\left(R_y - \Delta_z\right)\right]$$

Summing these four equations results in the first term Σt_z of the total torque equation:

$$\sum t_z = 4\frac{3\pi}{2}\left(-\sin^2(y)R_x + \sin^2(x)R_y\right)$$

Substituting the position vector $\boldsymbol{q}$ and force vector $\boldsymbol{r}$ components from **Table IV** into equation (4) results in the following total Z-axis torque equation:

$$\begin{aligned}T_z = \sum t_z &+ \left(\frac{-5\pi}{2} - x\right)\left(R_y + \Delta_z\right) + \left(\frac{5\pi}{2} + y\right)R_x \\ &+ \left(\frac{\pi}{2} - x\right)\left(R_y - \Delta_z\right) + \left(\frac{5\pi}{2} + y\right)R_x \\ &+ \left(\frac{-5\pi}{2} - x\right)\left(R_y + \Delta_z\right) + \left(\frac{-\pi}{2} + y\right)R_x \\ &+ \left(\frac{\pi}{2} - x\right)\left(R_y - \Delta_z\right) + \left(\frac{-\pi}{2} + y\right)R_x\end{aligned}$$

This equation simplifies to:

$$T_z = 4\left[\left(\frac{-3\pi}{2}\sin^2(y) + \pi + y\right)R_x + \left(\frac{3\pi}{2}\sin^2(x) - \pi - x\right)R_y - \frac{3\pi}{2}\Delta_z\right]$$

Input-Output Matrix for the Stage

Combining the three equations for total torque $\boldsymbol{T_x}$, $\boldsymbol{T_y}$, and $\boldsymbol{T_z}$ with the total force $\boldsymbol{F_x}$, $\boldsymbol{F_y}$, and $\boldsymbol{F_z}$ produced by the stage gives the following equation that represents the input-output behavior of the entire stage:

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{Bmatrix} = 4 \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \frac{-3\pi}{2}\sin(y)\cos(y)+z & \left(\frac{3\pi}{2}\sin^2(y) - \pi - y\right) & \frac{-3\pi}{2} & 0 & 0 \\ \frac{3\pi}{2}\sin(x)\cos(x)-z & 0 & \left(\frac{-3\pi}{2}\sin^2(x) + \pi + x\right) & 0 & \frac{-3\pi}{2} & 0 \\ \left(\frac{-3\pi}{2}\sin^2(y) + \pi + y\right) & \left(\frac{3\pi}{2}\sin^2(x) - \pi - x\right) & 0 & 0 & 0 & \frac{-3\pi}{2} \end{bmatrix} \begin{Bmatrix} R_x \\ R_y \\ R_z \\ \Delta_x \\ \Delta_y \\ \Delta_z \end{Bmatrix}$$

The equation can be rewritten as:

$$\mathbf{Y} = \mathbf{AU}$$

Matrix **A** is:

$$\mathbf{A} = \begin{bmatrix} 4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 \\ \times & \times & \times & -6\pi & 0 & 0 \\ \times & \times & \times & 0 & -6\pi & 0 \\ \times & \times & \times & 0 & 0 & -6\pi \end{bmatrix}$$

The "x" terms of matrix A are terms that depend only on the stage position. The total force produced by the stage depends only on the desired force vector $(\boldsymbol{R_x}, \boldsymbol{R_y}, \boldsymbol{R_z})$. Although the force vector affects the torque generated, the correction terms Δ_x, Δ_y, Δ_z can be used to generate desired and/or predetermined torques.

Torque Compensation

The method of the invention for independently controlling the forces and torque generated by the electric motor in six degrees of freedom preferably includes determining the uncompensated torque about the X, Y, and Z axis generated from the commutation scheme using the desired force vector $\boldsymbol{R}$ and then determining the correction terms Δ_x, Δ_y, Δ_z that make the total torque equal the desired value. The uncompensated torque about the X, Y, and Z axis generated

from the commutation scheme may be determined using force vector terms $\boldsymbol{R_x}$, $\boldsymbol{R_y}$, $\boldsymbol{R_z}$ and the lower-left nine elements of matrix $\boldsymbol{A}$. The correction terms Δ_x, Δ_y, Δ_z may be determined by dividing the desired torque minus the uncompensated torque about the X, Y, and Z axis by 6ĩ. The torque-compensated commutation equations thus uses the terms $\boldsymbol{R_x}$, $\boldsymbol{R_y}$, $\boldsymbol{R_z}$, Δ_x, Δ_y, and Δ_z.

FIG. 10 is a flow chart illustrating the process or method **250** of achieving motion of the magnet array **24** with respect to the coil array **22**. The method or process **250** begins at a start procedure **252**. Procedure **254** positions the magnet array **24** relative to the coil array **22**. Procedure **256** determines the position of the magnet array **24** relative to the coil array **22** with the use of a measurement device such as an interferometer. Procedure **258** energizes the active coils of the coil array **22** according to the commutation scheme as determined with the method described above. Procedure **260** determines whether a stop condition exists. If not, the method **250** returns to procedure **256** to determine the position of the magnet array **24** relative to the coil array **22**. If it is time to stop the motor, the method **250** terminates at a procedure **262**.

Procedure **258** controls the relative forces between a portion of the coil array and the moving magnet array by selectively applying predetermined currents to the appropriate coils such that the appropriate coils interact with the magnetic fields associated with the magnets in the magnet array and generate Lorentz forces.

As noted, the above-described method of independently controlling a moving magnet planar electric motor to position the platform in six degrees of freedom may be utilized with a moving coil electric motor. However, the commutation scheme is simpler because all the coils of the moving coil array are within the magnet field of the magnet array and no coils are partially within the magnet field. Thus, the forces generated between the coil and magnet arrays act through the center of the coils given that the coils are always in the same position relative to the center of gravity of the moving coil array or stage. Therefore, torque control is straightforward in a moving coil planar electric motor.

The electric motors of the invention may be used with a lithography system such as shown and described in, for example, the '118 patent referenced above. **FIG. 11** shows a schematic side view of an example of a photolithography system **800** using the electric motor **812** of the invention. Although the photolithography system **800** is described as utilizing a moving magnet electric motor **812**, the photolithography system may be adapted to utilize a moving coil electric motor or other variations of the moving magnet electric motor.

The photolithography system (exposure apparatus) **800** generally comprises an illumination system **802** (irradiation apparatus), a first frame **834**, a reticle stage assembly **810**, a second frame **832**, the optical assembly (lens assembly) **804**, a third frame **826**, and a wafer stage assembly **820**. A moving magnet electric motor **812** provided herein can be used as a part of the wafer stage assembly **820**. Alternately, with the disclosure provided herein, the moving magnet electric motor **812** can be modified for use as a part of the reticle stage assembly **810**.

The lithography system **800** is particularly useful as a lithographic device that transfers a pattern (not shown) of an integrated circuit from a reticle **806** onto a substrate such as a semiconductor wafer **808**. The lithography system **800** mounts to the mounting base **850**, e.g., the ground, a base, or floor or some other supporting structure.

The first frame **834** supports the illumination system **802** above the mounting base **850**. The second frame **832** supports the reticle stage assembly **810** above the mounting base **850**. The third frame **826** supports the optical assembly **804** above the mounting base **850**. The frames **834**, **832**, and **826** are coupled to the mounting base **850** by vibration damping devices **860**. The design of these frames **834**, **832**, and **826** can be varied to suit the design requirements for the rest of the lithography system **800**.

The illumination system includes an illumination source **851** and an illumination optical assembly **852**. The illumination source **851** emits a beam (irradiation) of light energy. The illumination optical assembly **852** guides the beam of light energy from the illumination source **851** to the optical assembly

804. The beam illuminates selectively different potions of the reticle **806** and exposes the wafer **808**. In Figure 8, the illumination system **802** is illustrated as being supported above the reticle stage assembly **810**. However, the illumination system **802** is secured to one of the sides of the frames and the energy beam from the illumination source **851** is directed to above the reticle stage assembly **810** with the illumination optical assembly **852**.

The optical assembly **804** projects and/or focuses the light passing through the reticle **806** to the wafer **808**. Depending upon the design of the lithography system **800**, the optical assembly **804** can magnify or reduce the image illuminated on the reticle **806**.

The reticle stage assembly **810** holds and positions the reticle **806** relative to the optical assembly **804** and the wafer **808**. Similarly, the wafer stage assembly **820** holds and positions the wafer **808** with respect to the projected image of the illuminated portions of the reticle **806** in the operation area. In Figure 8, the wafer stage assembly **820** utilizes the moving magnet electric motor **812** having features of the present invention. Depending upon the design, the lithography system **800** can also include additional wafer stage assemblies **820** to increase the throughput of the lithography system **800**.

The wafer **808** is held by vacuum suction on a wafer holder **849** that is supported on the wafer stage assembly **820**. The wafer stage assembly **820** is structured so that it can be moved in several (e.g., three to six) degrees of freedom by a planar motor (the moving magnet electric motor **812**) under precision control by a wafer stage driver **853** and system controller **855**, to position the wafer **808** at a desired position and orientation, and to move the wafer **808** relative to the projected image of the illuminated portions of the reticle **806** in the operation area. The moving magnet electric motor **812** comprises a moving magnet array **814** and a fixed coil array **818**. The moving magnet array **814** is connected to the wafer holder **849** and supported by air bearings **816** on a plate **836**. The plate **836** is positioned between the moving magnet array **814** and the fixed coil array **818** and connected to the third frame **826**. The plate **826** may be made of non-magnetic materials, for example, carbon fiber plastics, ceramics such as Zerodur

ceramics, Al_2O_3 ceramics, and like materials that do not impair the magnetic flux generated by the magnet array **814**. The plate **836** may be formed with a thick honeycomb structure or other types of reinforced structure to prevent it from bending. The coil array **818** is attached to the backing panel **822**. The backing panel **822** is rigidly supported on the mounting base **850** on support **861**. However, the baking panel **822** may be supported on the mounting base **850** by the vibration damping device **860** same as the frames **834**, **832**, and **826**.

The lithography system **800** includes a first measuring system that detects the position of the wafer holder **849** (wafer **808**) relative to the optical assembly **804** as a reference structure at least along the X, Y axis and about the Z (theta Z) axis. This information corresponds to the position of the magnet array **814** relative to the coil array **818**. The first measuring system can utilize an interferometer system. In this embodiment, the first measuring system comprises a first interferometer block **856** supported on the third frame **826** and a first moving mirror **857** attached to the wafer holder **849**. The first interferometer block **856** generates a pair of spaced apart laser beams (not shown) to the first moving mirror **857** and detects the beams reflected from the first moving mirror **857** to output the information of the position of the wafer 808 to the system controller **855**. Further, the lithography system **800** includes a second measuring system that detects the position of the reticle stage assembly **810** (reticle **806**) relative to the optical assembly **804** as a reference structure at least along the X, Y axis and about the Z (theta Z) axis. Somewhat similarly, the second measuring system comprises a second interferometer block **858** supported on the third frame **826** and a second moving mirror **859** attached to the reticle stage assembly **810**. The second interferometer block **858** generated a pair of spaced apart laser beam (not shown) to the second moving mirror **859** and detects the beams reflected from the second moving mirror **859** to output the information of the position of the reticle **806** to the system controller **855**.

The system controller **855** is connected to the first interferometer block **856**, the second interferometer block **858**, the wafer stage driver **853**, and a reticle stage driver **854**. The system controller **855** controls each of drivers **854** and **853**

for the reticle stage assembly **810** and wafer stage assembly **820** based on the information of the positions outputted from the interferometer blocks **856** and **858** and the desired position of the reticle and the wafer stage assemblies. In this embodiment, the system controller **855** determines current to be applied to coils included in the coil array **818** of the electric motor **812**, and outputs this information to the wafer stage driver **853**. The wafer stage driver **853** is connected to each coil of the coil array **818** and drives the electric motor **812** in accordance with the information. Further, the system controller **855** determines a resultant torque between the magnet array **814** and the coil array **818** and the correction current to compensate for the resultant torque as mentioned above. The wafer stage driver **853** drives the electric motor **812** based on this information. As a result, the wafer **808** is positioned precisely in wide ranges.

The electric motor **812** can be structured as the moving coil planar motor such as shown in **FIGS. 3** and **4**.

There are a number of different types of photolithographic devices. For example, photography system **800** can be used as a scanning type photolithography system which exposes the pattern from reticle **806** onto wafer **808** with reticle **806** and wafer **808** moving synchronously. In a scanning type lithographic device, reticle **806** is moved perpendicular to an optical axis of lens assembly **804** by reticle stage assembly **810** and wafer **808** is moved perpendicular to an optical axis of lens assembly **804** by wafer stage assembly **820**. Scanning of reticle **806** and wafer **808** occurs while reticle **806** and wafer **808** are moving synchronously.

Alternately, photolithography system **800** can be a step-and-repeat type photolithography system that exposes reticle **806** while reticle **806** and wafer **808** are stationary. In the step and repeat process, wafer **808** is in a constant position relative to reticle **806** and lens assembly **804** during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer **808** is consecutively moved by wafer stage assembly **820** perpendicular to the optical axis of lens assembly **804** so that the next field of semiconductor wafer **808** is brought into position relative to lens assembly **804** and reticle **806**.

However, the use of photolithography system **800** provided herein is not limited to a photolithography system for a semiconductor manufacturing. Photolithography system **800**, for example, can be used as an LCD photolithography system that exposes a liquid crystal display device pattern onto a rectangular glass plate or a photolithography system for manufacturing a thin film magnetic head. Further, the present invention can also be applied to a proximity photolithography system that exposes a mask pattern by closely locating a mask and a substrate without the use of a lens assembly. Additionally, the present invention provided herein can be used in other devices, including other semiconductor processing equipment, machine tools, metal cutting machines, and inspection machines.

The illumination source **851** can be g-line (436 nm), i-line (365 nm), KrF excimer laser (248 nm), ArF excimer laser (193 nm) and F_2 laser (157 nm). Alternatively, illumination source **851** can also use charged particle beams such as x-ray and electron beam. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB_6) or tantalum (Ta) can be used as an electron gun. Furthermore, in the case where an electron beam is used, the structure could be such that either a mask is used or a pattern can be directly formed on a substrate without the use of a mask.

With respect to lens assembly **804**, when far ultra-violet rays such as the excimer laser is used, glass materials such as quartz and fluorite that transmit far ultra-violet rays is preferably used. When the F_2 type laser or x-ray is used, lens assembly **804** should preferably be either catadioptric or refractive (a reticle should also preferably be a reflective type), and when an electron beam is used, electron optics should preferably comprise electron lenses and deflectors. The optical path for the electron beams should be in a vacuum.

Also, with an exposure device that employs vacuum ultra-violet radiation (VUV) of wavelength 200 nm or lower, use of the catadioptric type optical system can be considered. Examples of the catadioptric type of optical system include the disclosure Japan Patent Application Disclosure No. 8-171054 published in the Official Gazette for Laid -Open Patent Applications and its counterpart U.S.

Patent No. 5,668,672, as well as Japan Patent Application Disclosure No. 10-20195 and its counterpart U.S. Patent No. 5,835,275. In these cases, the reflecting optical device can be a catadioptric optical system incorporating a beam splitter and concave mirror. Japan Patent Application Disclosure No. 8-334695 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377 as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart U.S. Patent No. 873,606 (Application Date: 6-12-97) also use a reflecting-refracting type of optical system incorporating a concave mirror, etc., but without a beam splitter, and can also be employed with this invention. The disclosures in the above-mentioned U.S. patents, as well as the Japan patent applications published in the Official Gazette for Laid-Open Patent Applications are incorporated herein by reference.

Further, in photolithography systems, when linear motors (see U.S. Patent Nos. 5,623,853 or 5,528,118) are used in a wafer stage or a reticle stage, the linear motors can be either an air levitation type employing air bearings or a magnetic levitation type using Lorentz force or reactance force. Additionally, the stage could move along a guide, or it could be a guideless type stage which uses no guide. The disclosures in U.S. Patent No. 5,523,853 and 5,528,118 are incorporated herein by reference.

Alternately, one of the stages could be driven by a planar motor, which drives the stage by electromagnetic force generated by a magnet unit having two-dimensionally arranged magnets and an armature coil unit having two-dimensionally arranged coils in facing positions. With this type of driving system, either one of the magnet unit or the armature coil unit is connected to the stage and the other unit is mounted on the moving plane side of the stage.

Movement of the stages as described above generates reaction forces which can affect performance of the photolithography system. Reaction forces generated by the wafer (substrate) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction forces generated by the reticle (mask) stage motion can be

mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224. The disclosures in U.S. Patent Nos. 5,528,118 and 5,874,820 and Japanese Patent Application Disclosure No. 8-330224 are incorporated herein by reference.

As described above, a photolithography system according to the above described embodiments can be built by assembling various subsystems, including each element listed in the appended claims, in such a manner that prescribed mechanical accuracy, electrical accuracy and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, every optical system is adjusted to achieve its optical accuracy. Similarly, every mechanical system and every electrical system are adjusted to achieve their respective mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes mechanical interfaces, electrical circuit wiring connections and air pressure plumbing connections between each subsystem. Needless to say, there is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems, total adjustment is performed to make sure that every accuracy is maintained in the complete photolithography system. Additionally, it is desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

Further, semiconductor devices can be fabricated using the above described systems, by the process shown generally in **FIG. 12**. In step **401** the device's function and performance characteristics are designed. Next, in step **402**, a mask (reticle) having a pattern is designed according to the previous designing step, and in a parallel step **403**, a wafer is made from a silicon material. The mask pattern designed in step **402** is exposed onto the wafer from step **403** in step **404** by a photolithography system described hereinabove consistent with the principles of the present invention. In step **405** the semiconductor device is assembled (including the dicing process, bonding process and packaging process), then finally the device is inspected in step **406**.

FIG. 13 illustrates a detailed flowchart example of the above-mentioned step **404** in the case of fabricating semiconductor devices. In step **411** (oxidation step), the wafer surface is oxidized. In step **412** (CVD step), an insulation film is formed on the wafer surface. In step **413** (electrode formation step), electrodes are formed on the wafer by vapor deposition. In step **414** (ion implantation step), ions are implanted in the wafer. The above mentioned steps **411-414** form the preprocessing steps for wafers during wafer processing, and selection is made at each step according to processing requirements.

At each stage of wafer processing, when the above-mentioned preprocessing steps have been completed, the following post-processing steps are implemented. During post-processing, initially, in step **415** (photoresist formation step), photoresist is applied to a wafer. Next, in step **416**, (exposure step), the above-mentioned exposure device is used to transfer the circuit pattern of a mask (reticle) to a wafer. Then, in step **417**, (developing step), the exposed wafer is developed, and in step **418** (etching step), parts other than residual photoresist (exposed material surface) are removed by etching. In step **419** (photoresist removal step), unnecessary photoresist remaining after etching is removed.

Multiple circuit patterns are formed by repetition of these preprocessing and post-processing steps.

It will be apparent to those skilled in the art that various modifications and variations can be made in the methods described, in the stage device, the control system, the material chosen for the present invention, and in construction of the photolithography systems as well as other aspects of the invention without departing from the scope or spirit of the invention.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. For example, although depicted as being planar, the arrays of magnetic poles and coils can have either constant or varying curvature in one or two-dimensions as in cylindrical, toroidal, and spherical arrangements of magnetic poles and coils. For

cylindrical arrangements, latitudinal and longitudinal directions may be defined, for example, in standard cylindrical coordinates with corresponding diagonal directions, and parallel arrays and coils lie on parallel surfaces. Accordingly, all such modifications are intended to be within the scope of the following claims.